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Kun Peng

Institute of Blue and Green Development, Shandong University

Jiashuo Li

Institute of Blue and Green Development, Shandong University   https://orcid.org/0000-0002-2915-4770

Kuishuang Feng (✉ kfeng@umd.edu)

University of Maryland, College Park   https://orcid.org/0000-0001-5139-444X

Bin Chen

Fudan Tyndall Center, Department of Environmental Science and Engineering, Fudan University

Yuli Shan

University of Groningen   https://orcid.org/0000-0002-5215-8657

Ning Zhang

Shandong University

Peng Wang

Institute of Urban Environment

Kai Fang

School of Public Affairs, Zhejiang University

Yanchao Bai

College of Environmental Science and Engineering, Yangzhou University

Xiaowei Zou

Institute of Blue and Green Development, Shandong University

Article

Low carbon transition of global power sector enhances sustainable development goals

Kun Peng[1], Jiashuo Li[1, *], Kuishuang Feng[2, *], Bin Chen[3], Yuli Shan[4], Ning Zhang[1],

Peng Wang[5], Kai Fang[6], Yanchao Bai[7], Xiaowei Zou[1]

[1] Institute of Blue and Green Development, Shandong University, Weihai 264209,

China

[2] Department of Geographical Sciences, University of Maryland, College Park, MD

20742, United States

[3] Fudan Tyndall Center, Department of Environmental Science and Engineering,

Fudan University, Shanghai 200438, China

[4] Integrated Research on Energy, Environment and Society (IREES), Energy and

Sustainability Research Institute Groningen, University of Groningen, Groningen, the

Netherlands

[5] Key Lab of Urban Environment and Health, Institute of Urban Environment,

Chinese Academy of Sciences, Xiamen 361021, China

[6] School of Public Affairs, Zhejiang University, Hangzhou 310058, China

[7] College of Environmental Science and Engineering, Yangzhou University, Yangzhou

225127 China

Abstract: Low-carbon power transition, key to combatting climate change, brings far-reaching effects on achieving Sustainable Development Goals (SDGs), in terms of resources use, environmental emissions, employment, and many more. Here we assessed the potential impacts of power transition on 49 regional multiple SDGs progress under three different climate scenarios. We found that power transition could increase global SDG index score from 72.36 in 2015 to 74.38 in 2040 under the 1.5℃

27 scenario, compared with 70.55 and 71.44 under 'Coal-dependent' and 'Middle of the

28 road' scenario, respectively. The power transition related global SDG progress would

29 mainly come from switching to renewables in developing economies. Power transition

30 also improves the overall SDG in most developed economies under all scenarios, while

31 undermining their employment-related SDG progress. The global SDG progress would

32 be jeopardized by power transition related international trade changes under 'Coal-

33 dependent' and 'Middle of the road' scenario, while improved under the 1.5℃ scenario.

34 **Keywords:** low-carbon transition; Global power sector; SDGs; Climate scenarios

35

Introduction

The current fossil fuel-dominated power sector contributes for near 40% of global annual energy-related CO_2 emissions [1][2]. The low carbon transition of the power sector is crucial to tackling climate change and ensuring the future supply of energy [3,4]. According to the International Energy Agency (IEA), the climate target in the Paris Agreement that pursuing efforts to limit end-of-century warming to 1.5°C, cannot be achieved until the share of energy production from low-carbon energy technologies rising to 85% by 2040 [5].

However, power sector transition's impact is far beyond climate. It brings far-reaching effects on achieving Sustainable Development Goals (SDGs) [6], in terms of resources use[7,8], environmental emissions [3], employment [9], and many more[10,11]. What's more, power transition may reduce one problem while exacerbate others at times. For instance, the closure of coal-fired power plants will reduce cooling water withdrawal (advancing SDG 6: Clean Water and Sanitation) [12,13], but cause massive job losses in coal power industry and its various ancillary, upstream, and downstream industries (hindering SDG 8: Decent Work and Economic Growth) [14,15]. Expansion of low-carbon power such as wind power and solar energy as substitutes for fossil fuels can improve countries' ability to deal with climate change (advancing SDG 13: Climate Action) [16], while increases demand for critical materials (hindering SDG 12: Responsible Consumption and Production) [17,18].

56   Previous studies have primarily demonstrated the impacts of specific national or

57   regional power sector transition on a single aspect of sustainable development, such as

58   regional employment [19], economic growth [20], natural resources use [21,22], greenhouse gas

59   and pollutant emissions [23]. However, few have evaluated the environmental–social–

60   economic interrelationships (trade-offs or synergies) of the power sector transition and

61   its impacts on each region toward achieving the multiple SDGs simultaneously. The

62   lack of comprehensive assessment may lead to unintended consequences, or even

63   hinder some SDGs progress, when designing power transition pathways. For instance,

64   Wang et al. found that Developing Asia's long-term power plan featuring coal power

65   generation has not yet included the impact on regional sustainable use of water

66   resources, which may exacerbate its water shortage (hindering SDG 6: Clean Water and

67   Sanitation), if without any strategies to reduce cooling water use [24]. Additionally, power

68   transition in one region affects not only the local SDGs, but also SDGs progress in other

69   regions via inter-regional trade. The expansion of renewable power or the reduction of

70   fossil fuels in electricity mix in one country might lead to the changes of environmental

71   emissions, resources consumption, employment and value-added embodied in products

72   and services from global supply chains, thus potentially influencing other regions'

73   SDGs [25]. Some researchers have conducted initial investigations and found out that

74   European renewable energy directive will harm forests of tropical countries, such as

75   Indonesia and Brazil, through wood trade (hindering SDG 12: Responsible

76   Consumption and Production) [26]. Thus, we further highlight the role of international

77   trade in regional SDG progress for preventing the power transition at the expense of

78   SDG in other regions.

79   By applying Environmentally Extended Multiregional Input-Output Analysis

80   (MRIO) and SDG assessment approach, here, we examine the direct and supply-chain

81   effects of power transitions throughout the world on regional and global SDGs,

82   including the net environmental, social, and economic changes under three climate

83   mitigation scenarios ('Coal-dependent', 'Middle of the road' and 1.5℃ scenario) (**see**

84   **detailed explanations in Methods**). Our findings demonstrate that low carbon

85   transition of global power sector could enhance the overall SDG performance, but there

86   are huge differences across individual SDGs in different economies.

Results

The environmental and socio-economic impacts of global power sector transition
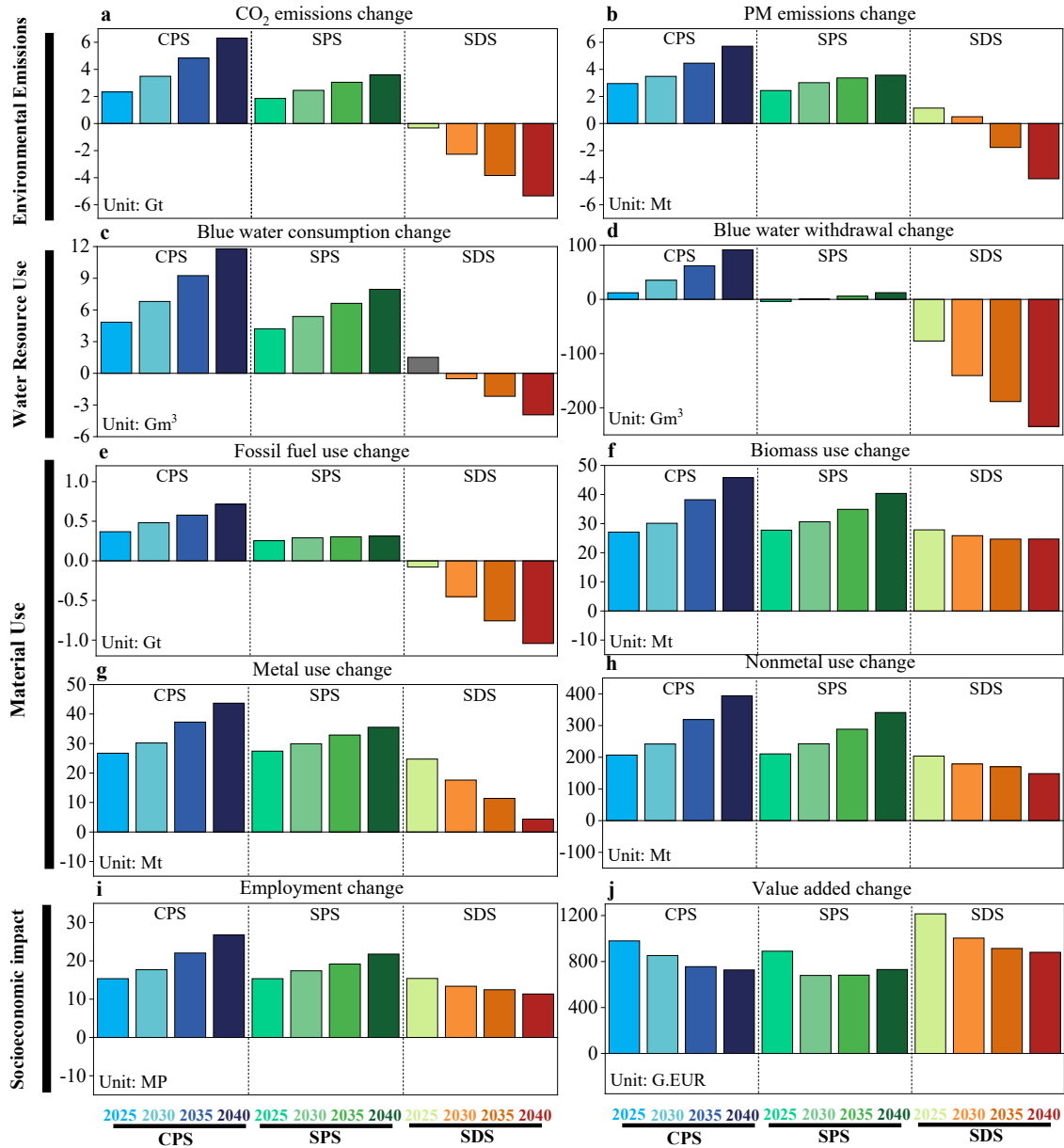
Figure 1. Comparison of the net changes in environmental and socio-economic impacts of global power sector in 2025-2040 under three different climate scenarios to that in 2015. (a-b) environmental emissions, **(c-d)** water resources use, **(e-h)** material use, and **(i-j)** socio-economic impacts. The three transition scenarios are Current Policies Scenario (CPS), Stated Policies Scenario

94　(SPS), and Sustainable Development Scenario (SDS), namely 'high coal' scenario, 'medium-sized

95　coal' scenario, and 1.5℃ scenario, respectively.

96　**Figure 1** shows the net changes of environmental emissions, water resources use,

97　material use, and socioeconomic impacts (the basic indicators to evaluate SDG progress)

98　associated with global power transition under three different climate scenarios-Current

99　Policies Scenario (CPS), Stated Policies Scenario (SPS), and Sustainable Development

100　Scenario (SDS), namely 'Coal-dependent', 'Middle of the road' and 1.5℃ scenario,

101　respectively.

102　From the figure we can see that global CO_2 emissions (**Figure 1a**) will increase

103　by 10% and 18% under CPS and SPS scenarios between 2015 and 2040, but decrease

104　by 15% under the SDS scenario. PM emissions (**Figure 1b**) show a similar trend with

105　relatively small absolute changes. The discrepancy of emissions under different

106　scenarios mainly results from the difference in energy mix of electricity production

107　(**Table S1-S3**).

108　For water use, scenario results showed a similar trend as the changes in

109　environmental emissions. Only SDS scenario results showed a significant annual

110　decrease of 3.93 Gm^3 (-0.33%) blue water consumption and 234.61 Gm^3 (-17.2%) blue

111　water withdrawal associated with power transition by 2040, compared with the increase

112　of water use under the CPS and SPS scenarios (**Figure 1c and 1d**).

113　Given the higher demand for electricity in the future, all scenarios results showed

114　an increasing use of materials, such as metal, non-metal minerals and biomass for power

115 transition, except a decrease of fossil fuels under the SDS scenario (**Figure 1e-h**).

116 However, compared with the CPS and SPS scenarios results, power sector would

117 consume much less materials under the SDS scenario.

118   In terms of socio-economic impacts of the power production and transition, we

119 can see a significant increase in both employment (**Figure 1i**) and value added (**Figure**

120 **1g**) under all scenarios, due to the high future demand of electricity. As coal power per

121 unit of installed capacity can generate more jobs than that of renewables, but drive less

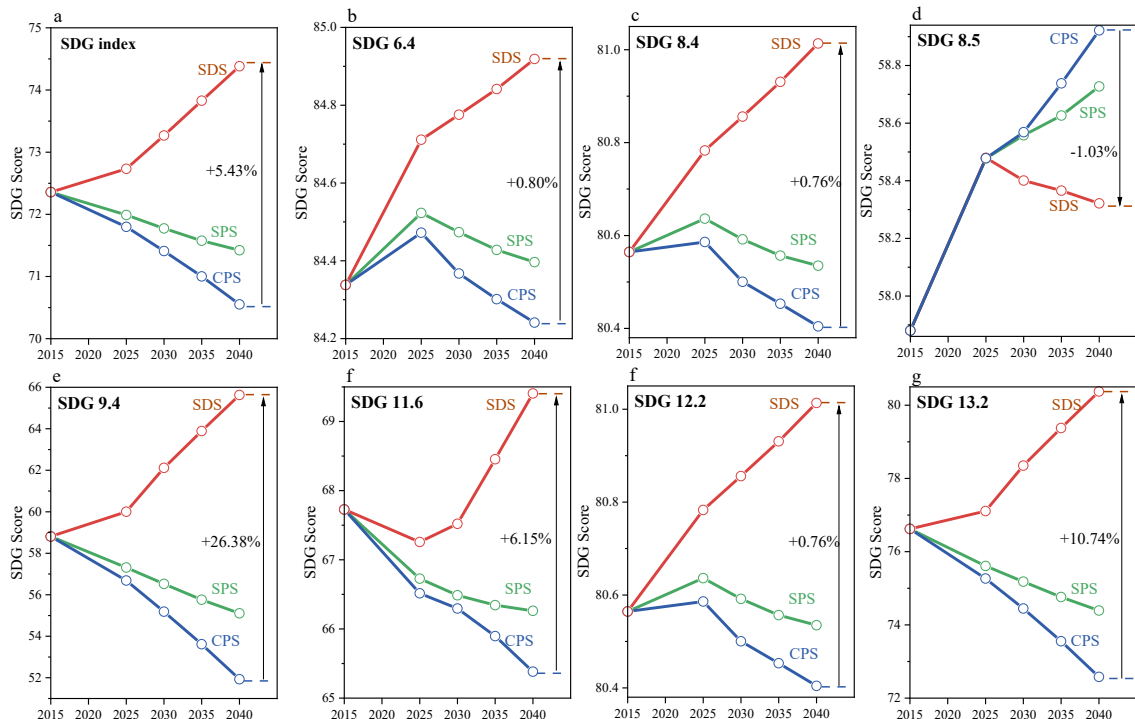122 economic output, our results showed that power generation and transition under the

123 SDS scenario (the most ambitious scenario with renewables generation) may bring less

124 job opportunities but create higher value added, compared with the results under CPS

125 and SPS.

126

127 **Power transition's impacts on global SDGs**

129 **Figure 2. Global SDG index score and individual SDG score under three different climate**

130 **scenarios. (a)** global SDG index score and (**b-h**) scores of SDG 6.4 (Ensure sustainable withdrawals

131 and supply of freshwater), SDG 8.4 (Improve resource efficiency in consumption and production),

132 SDG 8.5 (Achieve full and productive employment), SDG 9.4 (Promote clean and Sustainable

133 industrialization), SDG 11.6 (Reduce the adverse per capita environmental impact of cities), SDG

134 12.2 (Achieve the sustainable management and efficient use of natural resources) and SDG 13.2

135 (Integrate climate change measures into national policies, strategies and planning). **Note**: To ensure

136 comparability across different SDGs and different country/region, the SDG scores are normalized

137 to a standard scale ranging from 0 (worst-performing in achieving SDGs) to 100 (best-performing

138 in achieving SDGs).

139   Here, we translated the changes in environmental and social-economic indicators

140 into global SDGs progress using the United Nations SDG assessment approach (see

141 method section). Our results showed that the global SDG index score, defined as the

142 overall performance in achieving all individual SDG evaluated, will increase from

143 72.36 in 2015 to 74.38 in 2040 under SDS, while decrease to 70.55 and 71.44 in 2040,

144 under CPS and SPS, respectively (**Figure 2a**). The fossil fuel for electricity generation

145 plays a decisive role in global SDG performance of the power sector. As described in

146 our three scenarios, global SDG index score only rises when fossil power generation

147 drops (SDS), even though low-carbon power share will increase under each scenario.

148   Different power sector transition paths would undermine (**green and blue lines in**

149 **Figure 2**) or underpin (**red lines in Figure 2**) individual SDG progress (**Figures 2b-**

150 **2g**). In 2040, SDG 6.4, SDG 8.4, SDG 9.4, SDG 11.6, SDG 12.2 and SDG 13.2 present

151 higher scores under SDS scenario than the other two scenarios. The environmental and

152 socio-economic benefits from the low carbon transition (SDS scenario) are intrinsically

153 related to the reduction in blue water use, fossil fuels use, CO_2 and PM from the

154 shutdown of a large number of thermal power plants (see **Table S1-S4**). However, CPS

155 and SPS presents higher scores in SDG 8.5 (Achieve full and productive employment)

156 (**Figure 2d**). For example, in 2040, SDG 8.5 score under SDS (57.88) is less than 1.03%

157 of that under CPS (58.92). This is main because the shutdown of coal power under SDS

158 would lead to a large number of unemployment in both coal power generation and

159 upstream supply chains (e.g. coal mining sector).

160

161 **The impacts of power transition on regional SDGs**

162   SDG index score changes vary significantly across economies (**Figure. 3**). In

163 general, the higher the GDP per capita is, the more inclined an economy is to improve

164 the SDG index score and vice versa (**Table S4**). During the period of 2015-2040, the

165 average SDG index scores of developed economies will increase by 2 percentage points

166 and almost every developed economy improves their SDG scores to some extent under

167 the SDS scenario. However, close to 30% of the developed economies may face a

168 decline in their SDG scores under the CPS scenario. In contrast, more than half of the

169 developing economies, mainly from Asia and Africa, will have a decline in their SDG

scores under the CPS scenario, while this number decreased to about 20% under the

SDS scenario.
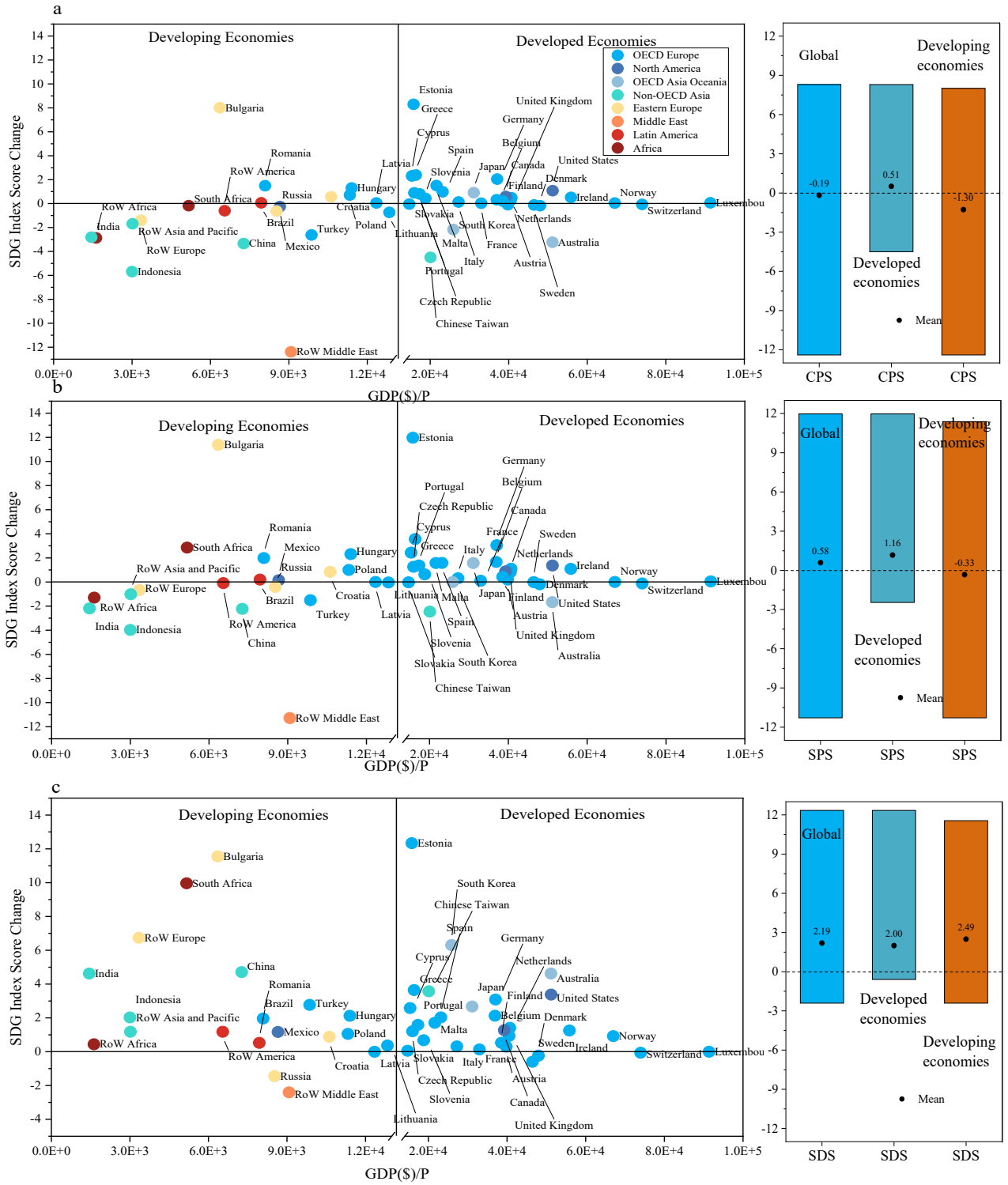
174   (**a**) changes under CPS, (**b**) changes under SPS, (**c**) changes under SDS and (**d**) score ranges and

175   mean score.

176

177   Estonia, one of the countries that most dependent on fossil power, is top economy

178   in SDG index score increase by 2040 under all scenarios, with a range of 8.29 to 11.33,

179   as it expects to significantly replace coal power through the development of renewable

180   energy such as wind power and biomass affected by European Climate Law. This

181   verifies that strict climate legislation can effectively improve the sustainable

182   development level of regions highly dependent on fossil power. In contrast, Middle East

183   is the economy with the biggest drops in SDG index score from 2.40 to 12.39, because

184   it will still develop gas power substantially.

185   SDS shows that regional power transition can also lead to synergies and trade-offs

186   between different individual SDGs (**Figure 4c**). As for synergies, more than 80%, 60%,

187   60%, 85%, 60%, and 80% of countries or regions will have an increase in SDG 6.4

188   scores, SDG 8.4/12.2 scores, SDG 8.5 scores, SDG 9.4 scores, SDG 11.6 scores, SDG

189   13.2 scores. However, there is a trade-off between SDG 8.5 and SDG index. For

190   example, under SDS, Bulgaria's SDG index score will increase by 11.55 in 2040, but

191   due to the loss of employment during the transition, its SDG 8.5 score fall by 0.05. In

192   addition, the power transition of some will increase all individual SDGs score, such as

193   United State, India, South Africa.

194
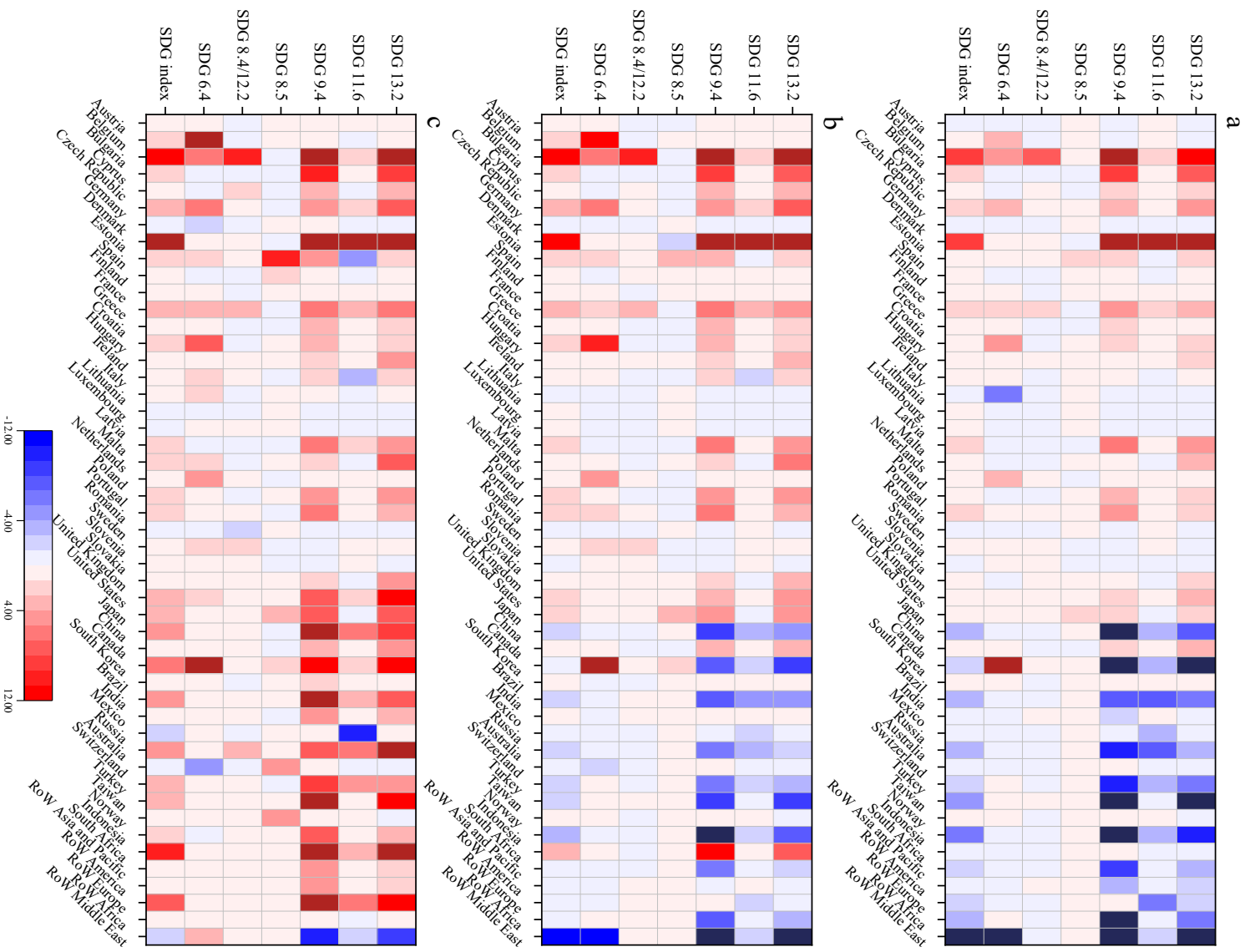
Figure 4. Changes of regional SDG index and individual SDG score between 2015 and 2040 under three scenarios. (a) CPS, **(b)** SPS, and **(c)** SDS.

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The effects of power transition related international trade changes on SDGs
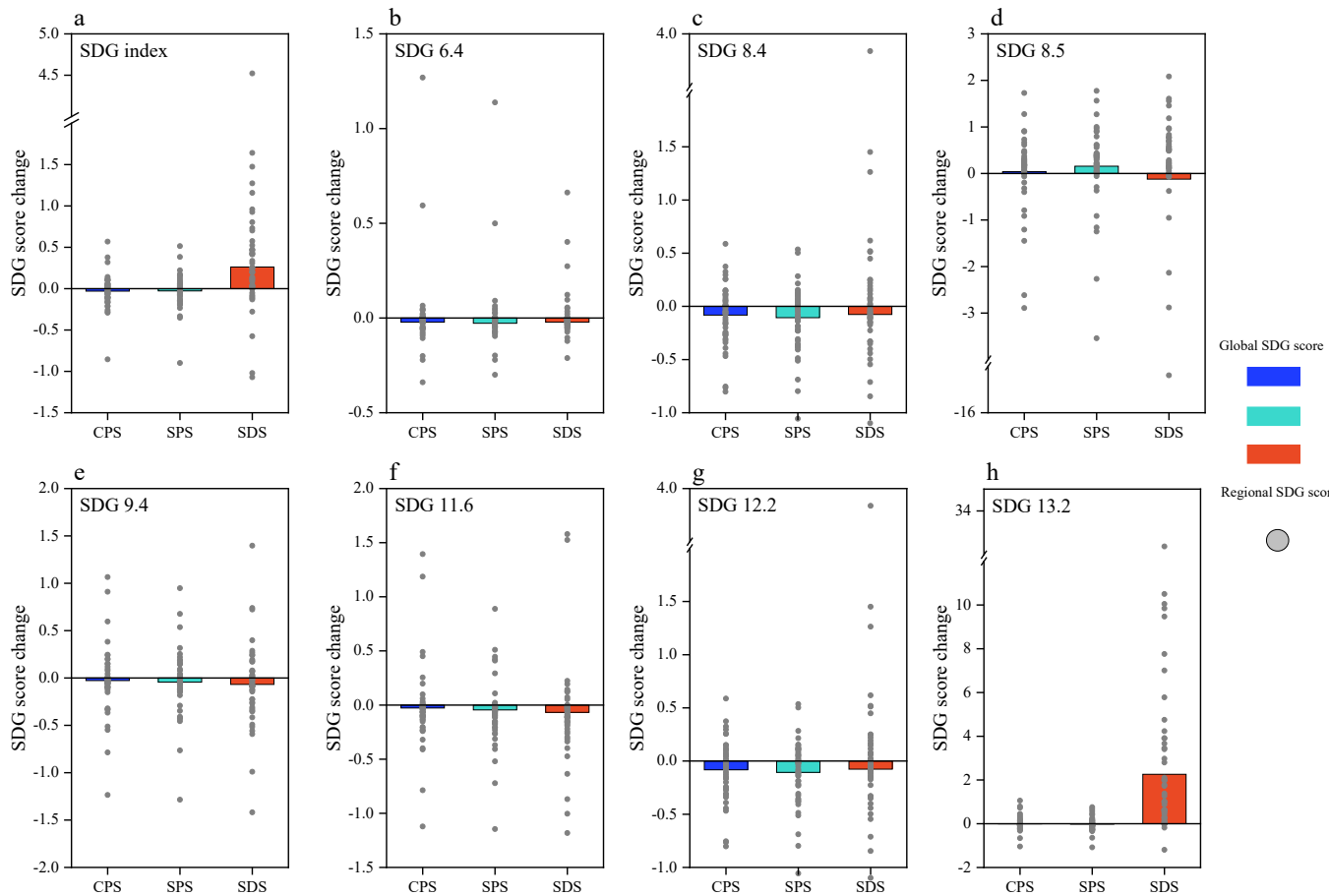
Figure 5. The impacts of power transition related international trade on global and regional

SDG performance between 2015 and 2040 under three different scenarios.

The power transition will change the scale and category of international trade for

renewable equipment and traditional power fuels between different economies and lead

to the changes in environmental emissions, resources consumption, employment and

value-added embodied in exports and imports, thus influencing SDG performance in

different regions. Under SDS scenario, the international trade will improve the overall

SDG performance (0.37%) globally between 2015 and 2040, while the results are

opposite (about -0.04%) under the CPS and SPS scenarios (**Figure 5a**). However, the

212   overall impacts of changes in international trade on the global SDG performance are

213   quite limited, as the traded commodities and services related to power sector only

214   account for less than 2% of the international trade, in terms of economic value. Climate-

215   related SDG (SDG 13.2) performance will have highest degree of improvement

216   (2.95%), mainly due to the reduction of CO_2 emissions embodied in thermal power-

217   related trade, under SDS (**Figure 5h**). Under CPS and SPS, the employment-related

218   SDG (SDG 8.5) performance will be improved (0.07-0.28%), mainly because of the

219   expansion of labor intensive renewable power sectors (**Figure 5d**). However, all

220   scenarios showed a decline (0.03-0.13%) in the average scores of resource-related

221   SDGs (SDGs 6.4, 8.4 and 12.2), due to the increase in power production related

222   resource use met by international trade (**Figure 5b, c and g**). The increasing resource

223   use for power transition may also lead to a decrease in the average scores of SDG 11.6

224   (Reduce the adverse per capita environmental impact of cities) by 0.04-0.1% under all

225   scenarios (**Figure 5f**).

226   From a regional perspective, more than 80% of economies would improve their

227   SDG performance under SDS (**Figure 5**). The countries/regions with rich fossil energy

228   resources, such as the Middle East, Czech Republic, Slovakia, ranked at the top in term

229   of SDG index score increase. This is mainly because other economies' low-carbon

230   power transition inevitably leads to the decrease of fossil fuel imported from these

231   regions, potentially reducing their resource extraction and related environmental

232   impacts. For example, under the SDS scenario, oil exports from the Middle East for

233   other economies' power production would be reduced by 65%, which result in a 0.28%

234   increase in its SDGs 8.4 (Improve resource efficiency in consumption and production)

235   score. In contrast, jobs will be wiped out in these fossil fuel export-dependent regions

236   such as Australia, as a result of the coal export deceases, therefore, leading to a 0.07%

237   of decrease in its employment-related SDG score (SDG 8.5). However, under CPS and

238   SPS, most of the individual economy's SDG progress (about 60%) would be impeded

239   by international trade, as the expansion of fossil fuel based power production leads to

240   the increase of power sector related resource consumption and environmental emissions

241   embodied in international trade. For instance, Russia, as a resource-rich economy, will

242   export more fossil resources to support power expansion of other economies, resulting

243   in an increase (about 7%) of carbon emissions embodied in its exports, and a decrease

244   (about 3%) of its climate-related SDG performance (**Table S5 and S6**).

245

246

247   **Discussion**

248   For the first time, we performed a quantitative analysis of power sector transition's

249   impacts on global and regional multiple SDGs performances. We found the evolution

250   of global SDG index score (the average score of seven selected SDGs) during 2015-

251   2040, is opposite under different climate scenarios. Power transition brings an increase

252   of 2.8% (72.36 in 2015 to 74.38 in 2040) in global SDG index score under the 1.5℃

253   scenario (i.e. SDS), while leads to a reduction of 1.3-1.5% (72.36 in 2015 to 70.55-

254   71.44 in 2040) under the 'high coal' and 'medium-sized coal' scenario (i.e. CPS and

255   SPS).

256   We also found that there are significant differences across regional SDG index

257   score changes. From 2015 to 2040, the regional SDG index score change is estimated

258   to be in the range of -12.39 (Row Middle East) to 8.29 (Estonia), -11.28 (Row Middle

259   East) to 11.97 (Estonia) and -2.4 (Row Middle East) to 12.33 (Estonia), under CPS,

260   SPS and SDS, namely 'Coal-dependent', 'Middle of the road' and 1.5℃ scenario

261   respectively. In addition, the change of regional individual SDG score isn't always

262   consistent with that of SDG index score. For instance, resource-related SDGs (SDGs

263   8.4 and 12.2) on 17 of the 49 economies, on the contrary, will become worse if the

264   currently fossil-dominated power structure transited to a renewable-dominated one (1.5℃

265   scenario).

266   According to Sustainable Development Report 2020, the progress of achieving the

267   SDGs by 2030 lags far behind the schedule predesigned by the UN [27]. One of the main

268   reasons is that there is a lack of understanding of the interactions between SDGs [28],

269   which is essential to trade-offs between SDGs and advance the overall SDGs with

270   minimal efforts[11]. As our research reveals the SDGs synergies and trade-offs in global

271   and regional power transition, which provide an insight into advancing the power

272   transformation and improving the current SDG "dilemma".

273

274   **Developing economies' lower carbon power transition is crucial**

275   Our results demonstrate that whether the global SDG performance can be

276   improved will be determined by developing economies' power transition. The main

277   reason is that fossil power contributed more than 70% of the electricity demand in

278   developing economies. As a result of gradual expansion in population and economy,

279   the electricity demand of developing economies will increase by 81.6-112.3% between

280   2015 and 2040, which is much higher than that of the developed economies (23.2-

281   28.4%) [5]. If power generation in developing economies is still dominated by fossil fuels,

282   there will be a large amount of greenhouse gas and pollutant emissions, as well as a

283   large amount of water resources and fossil fuels and minerals depletion, thus posing

284   great threats to global SDG progress.

285   To promote the clean and low carbon power transition in developing economies is

286   crucial to global SDG progress. Meanwhile, due to the different levels of economic

287   development and power structure, different developing economies need to take varying

288   measures.

289   For Africa, the continent with the lowest average income, the biggest challenge

290   facing transition is the lack of sufficient financial support [29]. For example, African low-

291   carbon electricity transition cannot be achieved until investments in power growing by

292   two-and-a-half times through to 2040, according to IEA. Given the limited financial

293   capacity and financial constraints of utilities of governments, private sources of finance

294   will be critical to bridge investment gaps. However, more than 1/3 of sub-Saharan

295   African countries such as Nigeria, Sudan do not allow for private sector participation

296   in electricity generation or networks, which greatly jeopardizes the decarbonization of

297   electricity in these areas [5]. For the smooth transition of the region, private investment

298   can be appropriately introduced.

299   For China and India, the two biggest coal-fired power producers in the world, a

300   rapid transition away from unabated coal use is essential. Recent regional trends reflect

301   a shift in coal power prioritization from the US and EU to many fast-developing

302   countries in Asia, especial in China and India [30]. Thus, specific policy efforts that target

303   coal-power production reduction are critical, for example, reductions in multilateral

304   development banks' financing of coal projects, national limits on coal consumption.

305   More importantly, the state needs to improve its commitment. China has come up with

306   clear carbon neutral targets and India needs to catch up.

307   **Measures to coordinate power transition and SDGs**

308   Transforming the power sector to low-carbon energy under the 1.5°C pathway (or

309   rapid low-carbon power transition) was verified that it can bring co-benefits to global

310   SDGs performance on the whole. However, the situation in each region differs from

311   one another. All individual SDGs in these nine economies, Australia, Ireland, United

312   States, Chinese Taiwan, RoW America, South Africa, RoW Europe, RoW Asia and

313   Pacific, India, can be advanced by rapid low-carbon power transition. This indicates

314   that the current and stated transition strategies of these countries are relatively

315   sustainable. However, it is worth noting that the power transition may lead to local SDG

316   conflicts in these economies. For example, the Indian government's clean energy

317   transition strategies (solar capacity addition targets are accompanied by the retirement

318   of thermal capacity) will create job opportunities primarily (60% of total) located in

319   western and southern parts of India (advancing SDG 8.5:Achieve full and productive

320   employment), while leading to job losses being concentrated in the coal-mining states

321   located in eastern India (hindering SDG 8.5) [31]. Thus, it is recommended a

322   comprehensive review of the cross-regional impact of the power transition in large

323   economies, such as the United States and India, to reduce regional imbalances from

324   transition. Meanwhile, specific development plans for sub-regional low-carbon power

325   transition are needed.

326   For most countries, the rapid low-carbon transition will cause conflicts between

327   individual SDGs progress (where progress in one goal hinders progress in another), so

328   thus hinder SDGs progress. For example, the expansions of wind power in Germany

329   will increase demand for metals and nonmetals, and undermine its SDG 8.4. In response

330   to the material requirement or bottleneck for the future deployment of low-carbon

331   power, it is critical to increasing secondary supply of materials (recycle) other than

332   exploiting mines. Given the low rate of recycling of materials and high recycling costs

333   in power sector, more efforts need to be exerted into the centralized recovery of retired

334   electrical equipment and the development of technologies that have lower costs and

335   higher recovery rates. The social justice issues come from laid-off workers caused by

336   the decommissioning of coal power plants. For example, 4.9 million coal power-related

337   workers will be unemployed in China in 2040 under SDS. Coal electricians and

338   upstream coal miners are difficult to get reemployed due to their limited skills. Coal-

339   transition support is, therefore, a necessary measure for coal workers and should be

340   considered by policymakers in coal-dependent countries.

341   Our results also indicate that international trade associated with the power sector

342   has a limited effect on the global overall SDG performance, but it will profoundly affect

343   the SDG process of individual countries. This means cross-national inequities in

344   achieving SDGs progress may be exacerbated as the expansion of renewable power or

345   the reduction of fossil fuels in the electricity mix. For example, under SDS, in 2040,

346   55.9% of metal use increases (hindering SDG 8.4 and 12.2) in the Row Europe are

347   caused by power transition in the country itself, and the remaining 44.1% are driven by

348   the other countries (advancing SDG 9.4 and 13.2) low-carbon transition's ripple effects

349   throughout global supply chains. This emphasizes power transition as a global systemic

350   phenomenon, instead of looking at the area of power installation in isolation, which

351   calls for taking consumption-based accounting principle into considering when

352   formulating power transition strategies to facilitate best practice in minimizing impacts

353   on SDG.

354   **Limitations and future works**

355   This study employed the labor data in EXIOBASE 3 to analyze the impact of

356   power transition on regional employment. Although this data is more detailed on sector

357   classification than other authority's data, such as International Labor Organization, it

358   divides the broad renewable sector's employment into detailed industries (such as wind

359   power, PV) according to their shares in total compensation of employees, and does not

360   distinguish the employment coefficients difference between different renewable power

361   sectors. This may leave uncertainty in our employment accounting in renewable sectors.

362   In future research, more detailed employment survey data in renewable sectors is

363   needed to reduce the uncertainty of analyzing power transitions' impact on employment.

364   Moreover, the power transition is part of the energy transition, which also includes

365   industry and residential sectors' transition etc. Combining with the foundation lied by

366   this study, future studies can focus on much bigger picture, try to reveal the entire

367   energy system transition's influence on SDGs performance.

368

369   **Methods**

370   **Three climate scenarios**

371   The three climate scenarios (Current Policies Scenario, Stated Policies Scenario, and

372   Sustainable Development Scenario, namely 'Coal-dependent', 'Middle of the road' and

373   1.5°C scenario, respectively) were derived from the latest IEA's Word Energy Outlook

374   report. Current Policies Scenario is the most fossil-dependent scenario, in which coal-

375   fired electricity generation, with an amount of 12923 TWh, accounts for 30% of

376   electricity supply and gas-fired generation for about 25% by 2040. Under Stated

377   Policies Scenario, coal-fired electricity generation's share of overall generation will

378   decline from 38% to 25% and the share of generation from renewables increases from

379   26% today to 44% in 2040, with solar PV and wind together rising from 7% to 24%.

380   Sustainable Development Scenario has the most ambitious scenario with renewables

381   generation to keep global temperature rise below 1.5°C above the pre-industrial level.

382   The growth of renewables generation raising their share of generation to two-thirds by

383   2040. Wind and solar PV together provide 40% of generation in 2040. More details

384   about the three scenarios can be found in the IEA's Word Energy Outlook.

385   **Indicator selection and data sources for SDG**

386   The indicators selected for SDG in this study were from *the Global Indicator*

387   *Framework for Sustainable Development Goals* developed by the United Nations'

388   Inter-Agency and Expert Group on SDG Indicators [32], two reports titled "*Indicators*

389   *and a Monitoring Framework for the Sustainable Development Goals*" and

390   "*Sustainable Development Report 2020*" published by the United Nations' Sustainable

391   Development Solutions Network [27,33], and a study entitled "*Assessing progress towards*

392   *sustainable development over space and time*" published in Nature [34]. We chose SDG

393   indicators based on the following three criteria: (1) the indicators are likely to be

394   affected by electricity transition, (2) the indicators can be quantified across

395   organizational levels and temporal scales, and (3) the data for quantifying the indicators

396   are available from EXIOBASE[35] (see more detail about EXIOBASE in the next

397   paragraph).

398   **Calculating the scores of selected SDG indicators**

399   Using 2015 as baseline year, we calculated the score of selected SDG indicators

400   for all 49 countries/regions in EXIOBASE 3. The procedure comprised following steps:

401   To ensure data comparability across different SDG indicators, each indicator data was

402   rescaled from 0 to 100, with 0 indicating worst performance and 100 denoting the

403   optimum. Given rescaling is very sensitive to extreme (outliers) values on both tails of

404   the data distribution, we followed the methods proposed by *Sustainable Development*

405   *Report 2020* to determine the upper bound and low bound of each SDG indicator. We

406   defined the data at the bottom 2.5[th] percentile of all economies' SDG indicator

407   performances for a given SDG indicator as the minimum value (0) and the data at the

408   upper 2.5th percentile as the maximum value (100) for the normalization, for removing

409   the effect of extreme values. In addition, we used net CO_2 emissions to set a 100%

410   upper bound for SDG 9.4 and 13.2, as it must be achieved. After determining the upper

411 and lower bounds, we rescaled the selected SDG indicator values across economies to

412 a scale of 0 to 100 with equation (1):

413
$$Z' = \frac{Z - min(Z)}{max(Z) - min(Z)} \times 100 \qquad (1)$$

414 where Z represents the raw data value for a given SDG indicator. Min and max is the

415 bounds for the worse and best performance, respectively. Z' denote the normalized

416 value for a given SDG indicator.

417 **MRIO analysis for estimating the impacts of electricity transition on SDG**

418 **progress**

419 First, we applied Input-Output analysis (IOA) to quantifying the environmental-

420 social-economic impact of power sector in 2015. This model captured both direct and

421 indirect effects of eleven electricity production sub-sectors (including coal power, gas

422 power, nuclear power, hydroelectricity, wind power, petroleum and other oil derivatives

423 power, biomass and waste power, solar photovoltaic, solar thermal, tide, wave, ocean

424 power, and geothermal power) on environmental emissions, water resources use,

425 material use, employment and value-add. The basic framework of IOA is as follow:

426
$$X = (I - A)^{-1} Y \qquad (2)$$

427 where $X = \left[X_i^r \right]_{n \times 1}$, X_i^r is the total output of ith sector in region r. I is the identity

428 matrix. $A = \left[A_{ij}^{rs} \right]_{n \times n}$ is the technical coefficient matrix, A_{ij}^{rs} is given by

429 $A_{ij}^{rs} = Z_{ij}^{rs} / X_j^s$, in which Z_{ij}^{rs} represents the monetary value flows from ith sector in

430 region r to jth sector in region s and X_j^s is the total output of jth sector in region s.

431 $Y = \left[Y_i^{rs} \right]_{n \times m}$ is the final demand matrix, Y_i^{rs} represents the final demand of region

432 s for the goods and services of ith sector from region r.

433 Total (including direct and indirect) environmental-social-economic impact of one

434 of electricity production sub-sectors can be mathematically expressed as:

$$R = f(I - A)^{-1} X'$$ (3)

436 where f is a matrix of the environmental emissions, water resources use, material use,

437 employment and value-add intensity (the direct environmental emissions, water

438 resources use, material use, employment and value-add per unit total output from each

439 sector) for all economic sectors in all regions. X' is the total output matrix with zeros

440 for all sectors' total output other than the electricity production sub-sectors.

441 In addition, we define the difference between the total impact and the direct impact

442 (E, the direct environmental emissions, water resources use, material use, employment

443 and value-add) as the impact of trade (T).

$$T = R - E$$ (4)

445 **Declaration of Interests**

446 The authors declare that they have no competing interests.

447

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451 **Table 1 Indicators selected for quantifying the impacts of power transition on SDG**

No.	SDG Indicators	SDG indicators illustration
1	SDG 6.4 Ensure sustainable withdrawals and supply of freshwater	6.4.1 Water-use efficiency: blue water consumption per GDP
		6.4.2 Level of water stress: blue water withdrawal as a proportion of available freshwater resources
2	SDG 8.4 Improve resource efficiency in consumption and production	8.4.1 (1) Domestic material use per capita: metal use per capita
		8.4.1 (2) Domestic material use per capita: non-metallic minerals use per capita
		8.4.1 (3) Domestic material use per capita: fossil fuels use per capita

26

		8.4.1 (4) Domestic material use per capita: biomass use per capita
		8.4.2 (1) Domestic material use per capita: metal use per GDP
		8.4.2 (2) Domestic material use per capita: non-metallic minerals use per GDP
		8.4.2 (3) Domestic material use per capita: fossil fuels use per GDP
		8.4.2 (4) Domestic material use per capita: biomass use per GDP
3	SDG 8.5 Achieve full and productive employment	8.5 Unemployment rate (% total labor force)
4	SDG 9.4 Promote clean and Sustainable industrialization	9.4 CO_2 emissions per unit of value added
5	SDG 11.6 Reduce the adverse per capita environmental impact of cities	11.6 Annual mean levels of fine particulate matter (e.g. PM2.5 and PM10) in cities (population weighted)
6	SDG 12.2 Achieve the sustainable management and efficient use of natural resources (same indicators in the official indicator book: 8.4.1/12.2.1, 8.4.2/12.2.2)	12.2.1 (1) Domestic material use per capita: metal use per capita
		12.2.1 (2) Domestic material use per capita: non-metallic minerals use per capita
		12.2.1 (3) Domestic material use per capita: fossil fuels use per capita
		12.2.1 (4) Domestic material use per capita: biomass use per capita
		12.2.2 (1) Domestic material use per capita: metal use per GDP
		12.2.2 (2) Domestic material use per capita: non-metallic minerals use per GDP
		12.2.2 (3) Domestic material use per capita: fossil fuels use per GDP
		12.2.2 (4) Domestic material use per capita: biomass use per GDP
7	SDG 13.2 Integrate climate change measures into national policies, strategies and planning	13.2.1 CO_2 emissions intensity of forest areas
		13.2.2 CO_2 emissions intensity per capita
		13.2.3 CO_2 emissions intensity per GDP

452

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